METAMORPHIC STUDIES[1]

CONVERGENCE TO MINERAL TYPE IN DYNAMIC METAMORPHISM

C. K. LEITH AND W. J. MEAD
University of Wisconsin

The thesis of this paper is that the formation of slates, schists, and some gneisses, by rock flowage, requires both mineralogical and chemical changes, and that there is convergence, both chemically and mineralogically, toward a comparatively few platy or columnar minerals, tending to give these rocks their characteristic lamellar structure. If such convergence can be demonstrated, it may be used as a guiding principle in the study and interpretation of this phase of metamorphism. In this paper it is proposed to discuss anamorphism from this point of view.

Mineral changes in anamorphism by rock flowage.—It is generally recognized, and need not here be demonstrated, that anamorphism by rock flowage tends to produce platy and columnar minerals, like mica, chlorite, hornblende; that these increase at the expense of other minerals during the process, and that in the resulting slates, schists, or gneisses, they are the characteristic minerals which determine the lamination and cleavage of the rock and give the rock its name. Quartz and feldspar are also important minerals in the slates, schists, and gneisses, but these minerals are less important than the first-named group in producing the essential characteristics of the slates, schists, and gneisses, and they tend to diminish relatively in quantity in proportion as platy and columnar minerals increase. Mica, chlorite, hornblende, feldspar, and quartz make up all but an insignificant part of the mass of schists, slates, and gneisses. There are of course other minerals developed, such as garnet, staurolite, chloritoid, sillimanite, andalusite, etc., which in certain rocks may be conspicuous and

[1] See also C. K. Leith, "The Metamorphic Cycle," *Jour. Geol.*, XV (1907), 303–13; C. K. Leith and W. J. Mead, "Metamorphic Studies," *ibid.*, XX (1912), 353–61; C. K. Leith and W. J. Mead, *Textbook of Metamorphism* (in press, Henry Holt & Co.).

distinctive, and therefore are used in naming the rock, but in abundance they must be regarded as distinctly minor and accessory constituents as compared to the principal constituents before named.

In the progressive changes from a mud or clay to a shale and in turn to a slate or schist, there is an increase in the percentage by weight of mica and chlorite with relative decrease of other constituents. Muscovite or sericite makes up from a third to a half of mica slates, according to Dale,[1] and in a phyllite may be in even larger proportion, whereas in the original rock the percentage was but a small fraction of this amount. There is corresponding decrease in kaolin, feldspar, and certain ferromagnesian minerals.

Where a sandstone or quartzite becomes schistose there is an increase of mica, with corresponding decrease of other constituents. Certain specific instances of development of sericite schists in shear zones crossing the bedding of a quartzite have shown elimination of the greater part of the quartz of the original rock, due to solution, probably aided greatly by minute granulation.

A limestone or a marble may become schistose purely by process of granulation, which involves no essential development of new minerals. But more often there is a striking development of amphibole and other silicates with a corresponding diminution in calcite. Silicated marbles, resulting from metamorphism, are too well known to need further description.

A granite, by metamorphism during rock flowage, may become a mica schist or mica gneiss. Mica is increased at the expense of the feldspar and some of the ferromagnesian minerals.

A basic igneous rock, by dynamic metamorphism, may become a chlorite or hornblende schist or gneiss, the increase of chlorite or hornblende being counterbalanced by decrease in feldspar and pyroxene.

The average igneous rock, according to Clarke,[2] has about 60 per cent feldspar, 28 per cent ferromagnesian and accessory

[1] T. Nelson Dale, "Slates of the United States," *Bull. 586, U.S. Geol. Survey*, 1914, p. 20.

[2] F. W. Clarke, "The Data of Geochemistry," *Bull. 491* (2d ed.), *U.S. Geol. Survey*, 1911, p. 398.

minerals, and 12 per cent quartz. The schists or gneisses developed from these igneous rocks have a considerably smaller proportion of feldspars. The ferromagnesian minerals, instead of consisting dominantly of augite and biotite, with some muscovite, are now largely hornblende and muscovite, with subordinate quantities of biotite.

Whether the parent rock is igneous or sedimentary, or whatever its mineral content, the resulting schists and gneisses are characterized by hornblende, chlorite, and mica, which are developed to such an extent that the very nature of the original rock is often lost. If the mineralogical change were not extensive, the problem of origin of schists and gneisses would not be nearly so difficult as it is. The very existence of the problem testifies to the great mineralogical changes which have occurred. A sericite schist, for instance, may result from dynamic anamorphism of a slate, an igneous rock, or a quartzite. A hornblende schist may result from the anamorphism of a limestone or marble or may develop from a basic igneous rock, a graywacke or other basic sediment, or a slate.

A few distinctive minerals, such as mica, chlorite, and hornblende, are the characteristic resulting products of anamorphism by rock flowage of a considerable variety of parent rocks. In this sense, then, there is a convergence toward a certain mineralogic type.

Chemical changes during anamorphism by rock flowage.—When the chemical changes in anamorphism by rock flowage are considered, there is less general acceptance of the fact that actual changes in composition take place and that these changes are in the direction of producing the composition of the characteristic minerals in the end-products. Probably it is the general view that the conditions of rock flowage and anamorphism are not usually favorable to extensive transfers of materials involved in change of composition. It is often true that there are no important changes in percentages of chemical constituents during the process of rock flowage and anamorphism, the mineralogical change having been accomplished through recrystallization of substances present. This is especially true when the original rocks are well adapted, in

their composition, like shales, to the production of the necessary schist-making minerals. But even in these cases the elimination of water, carbon dioxide, and oxygen is recognized. We think it can be likewise inferred, in cases where the composition of the parent rock differs widely from the composition of the hornblende, mica, or chlorite, that important chemical changes take place, principally by the elimination of the substances present in excess of these requirements, but possibly also in some cases by addition of substances from without, and that there is therefore a chemical as well as mineralogical convergence toward mineral types.

Illustrative of such changes is the diminution of carbon dioxide, and perhaps lime, when a marble becomes silicated. In extreme cases an amphibolite has been described as the end-result of the alteration of marble. This obviously means a considerable change in chemical composition. For the purposes of our argument it is immaterial whether this change consists dominantly of elimination or of substitution of constituents from without along igneous contacts. Rock flowage and anamorphism are often accomplished under conditions which make it impossible to determine the relative importance of the purely mechanical and of the igneous influence respectively in their production. The point we would emphasize is that the characteristic product like amphibolite or silicated marble resulting from rock flowage or anamorphism differs distinctly in composition from the primary limestones or marble.

The development of talc schist from the anamorphism of a dolomite indicates an important change of composition, like that in the Menominee district of Michigan.[1]

A quartzite often becomes sheared and transformed into a sericite schist. Where shearing follows impure phases of the quartzite parallel to the bedding, it is difficult to prove any change in composition, but where the sericite schist develops in shear zones, crossing massive beds of quartzite, and samples can be collected showing complete gradation of the massive quartzite into the sericite schist, there is conclusive evidence of the elimination of quartz. The authors have carefully sampled two good cases of

[1] W. S. Bayley, "Menominee Iron-bearing District of Michigan," *Mon. 46, U.S. Geol. Survey*, 1904.

this kind in the Marquette district of Michigan. Another case is worked out in similar fashion by J. H. Warner on the Waterloo quartzite of Wisconsin, where shear zones cross the bedding. Analyses of these rocks,[1] show that the larger part of the free quartz has been eliminated, presumably through solution aided by granulation.

Where shales are traced into slates or schists the change in composition is less obvious, owing to the fact that the shale originally possesses pretty nearly the composition required by the end-products, but even here, important changes in composition are noted, like the elimination of CO_2, water, and oxygen, and, in some cases, the increase of potash.

A greenstone in the Marquette district of Michigan has been traced inch by inch into a sericite-chlorite schist and sampled on a large scale, the resulting analyses showing elimination of silica, an increase of alumina and ferric oxide, potash, and a considerable decrease in lime. Similar changes are described and analyzed by George H. Williams.[2]

It is not easy to find in the field satisfactory gradations from massive to schistose rocks where one can be certain that the mass was throughout of uniform composition. It is still more rare that these gradations have been thoroughly sampled so that the analyses furnish an adequate basis for comparison. It is significant, however, that where this has been done—and we have searched the literature carefully—important changes are to be noted.

Fortunately we are not obliged in our conclusion to rely entirely on the few well-sampled gradations from primary to schistose rock. A study of the actual compositions of the principal groups of schists brings out the fact that these vary in certain essential respects from those of the primary rocks from which they are supposed to have been derived. In another discussion[3] of the use of chemical criteria in the identification of schists and gneisses,

[1] C. K. Leith and W. J. Mead, *Textbook of Metamorphism* (in press, Henry Holt & Co.

[2] G. H. Williams, "The Greenstone Schist Areas of the Menominee and Marquette Regions of Michigan; A Contribution to the Subject of Dynamic Metamorphism in Eruptive Rocks," *Bull. 62*, *U.S. Geol. Survey*, 1890.

[3] *Textbook of Metamorphism*, cited above.

analyses of common schists have been platted graphically in order that they may be compared with both known and possible parent rocks. An examination of these plates brings out the fact that the composition of the schist tends to approach the distinctive chemical characteristics of the dominant platy or columnar mineral in the schist. This is especially well shown in the sericite schist, the composition of which lies between that of the primary rock and that of the mineral sericite. It is indicated, not only by the position of the analyses on the diagram, but by the shapes of the flags showing the relative amounts of constituents. If we were to include in these plates only those schists in which the processes of anamorphism and rock flowage have gone to an extreme, the tendency would be still more obvious, because rocks are included in these diagrams, described as hornblende, chlorite, or mica schist, which have but a small proportion of these minerals.

Our inference from the available facts is that, while recrystallization of substances present has of course played an important part in the production of schists, for some rocks important changes in composition have also occurred; that these changes in composition have been toward the composition of the characteristic end-products—mica, hornblende, or chlorite; that these changes are known both in sedimentary and in igneous rocks, of both acid and basic composition, and that the changes have been sufficiently important to make it impossible, along with other reasons, to use chemical composition as a conclusive criterion for the identification of origin of schists and gneisses.

Significance of convergence.—If this idea of convergence be correct, our attention is directed to the physical and chemical characteristics of a few minerals like mica, chlorite, and hornblende as important factors in anamorphism by rock flowage. Obviously they are adapted to the conditions of rock flowage; otherwise they would not develop at the expense of other minerals. It is not so clear whether they are adapted by their crystal habits, by their cleavages, by their composition, or by a combination of these characters. The fact that they are always arranged according to their dimensions, their greatest and least mean being respectively parallel, and the fact that their dimensions in the schist are clearly those

determined by their habit of crystal growth, rather than by any growth or breaking giving other shapes, direct our attention to the crystal habit of these minerals as essential reasons for their development. Whether processes of rock flowage have been weak or intense, the resulting minerals maintain their habit and dimensional characteristics.

If convergence toward certain characteristic minerals is established in rock flowage, the question naturally arises whether these end-products can be regarded purely as results of the great variety of processes in anamorphism by rock flowage, or whether the individual characters of the resulting minerals have exerted a certain directive and controlling influence in converging the various lines of anamorphism and rock flowage toward themselves, and more particularly whether the crystal habit of these minerals has exerted this influence. From this point of view it seems to be something more than a coincidence that, under such a variety of conditions and with such variety of available materials, that which we call crystallizing force has been able to exert itself to the extent of causing important mineralogical and chemical changes toward a limited number of mineral forms. It has drawn to itself the materials needed, eliminated those not needed, and has developed crystals of uniform habit. Under given environment it has had the capacity to organize the substances in a fashion best adapted to environment in much the same way that organisms have been supposed to adapt themselves to environment. The problem before us may be similar to the biologic question whether organisms are distinctly the results of physical and chemical environment or whether that mysterious force we call life on occasion rises superior to environment and to some extent modifies and controls external conditions. It is sometimes said that man is the multiplier and environment the multiplicand in the product determining history. The attempt to apply the same reasoning to the development of certain characteristic minerals in schists suggests the crystallizing power of these crystal individuals as the multiplier and environment as the multiplicand in the product representing rock flowage.

It is of interest also to note that the convergence here argued is toward a group mineralogically and chemically different from

primary igneous rocks, from which all metamorphism presumably starts, and is essentially a by-product of the metamorphic cycle. The difference between schists, gneisses, and slates, on the one hand, and igneous rocks on the other, represents a gap which has not been closed by the metamorphic cycle. The schists, gneisses, and slates represent types which are clearly nearer the composition of the original igneous rock than many of the rocks, particularly the sediments, which have been anamorphosed and recrystallized and have undergone rock flowage.

This convergence toward igneous rock composition often reaches a point where chemical criteria are not sufficient to determine whether or not the primary rock was igneous or sedimentary, the resulting composition being so nearly that of an igneous rock. If, along igneous contacts, a considerable amount of material has been completely fused, the anamorphic product may take on the character of an igneous rock and in such places the cycle is closed. But just as sandstones or limestones may be regarded as products of the cycle, some of which never go back to their primary condition of igneous rocks, so the schists and gneisses are by-products, which do not go back to the condition of igneous rocks under ordinary conditions of anamorphism. Whether the cycle in its larger aspects is completely closed, so far as the great mass of products is concerned, is a very doubtful question which has been discussed in a previous paper.[1]

[1] *Jour. Geol.*, XX (1912), 353–61.